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TESTS AND EVALUATIONS OF CLOSE-IN DETONATIONS

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Abstract

Some close-in detonation tests conducted in the FRG are described and methods to determine the loading caused by blast and fragmentation are mentioned. After establishing the load the local damage effects are explained theoretically. The problem of determining the blast load caused by cased cylindrical charges as well as the question of pressure waves caused by fragmentation is mentioned. Finally the question of scaling fragmentation effects is considered.

1. Introduction

Late in 1981 and in summer 1982 Federal Armed Forces Office for Studies and Exercises - Special Infrastructure Tasks Division - did some experimental work concerning upgrading of underreinforced concrete walls of semihardened structures against a given threat (Ref. 5 and 6). This test series seems to be a good experimental baseline for the subject I am going to deal with. However, I am not going to talk about the different upgrading systems we tested and we finally recommended. This can be taken from the references given above. But what makes this series so important for us is the fact that we have been forced to identify the damage mechanism against which we tried to provide protection. Thus, I am going to present the tests performed on walls without upgrading only, totalling 6 shots out of about 25. 5 of those 6 shots were scaled tests and 4 of the 6 shots were conducted with a cased weapon.

One of the structures which was tested is shown in Fig. 1. The clear height of the wall was 1.75 m. The percentage of the vertical reinforcement was 0.085% for walls No. 3 and 4 and 0.17% for walls No. 1 and 2 with a steel quality of 500/550 N/mm^2 and 420/500 N/mm^2 respectively, according to German Standards. The concrete compressive strength was about 25N/mm^2 for the first test and 40N/mm^2 for the other tests.

2. Brief Description of the Tests

Fig. 2 shows a test with 26.6 kg C4. Using an equivalent weight factor of 1.3 the scaled distance was 0.46m/kg$^{1/3}$. As it can be seen the wall was breached over an area of about 1.5 m width and 60 cm height. The first spalling layer was about 10 to 12 cm thick.

Fig. 3 shows another test with an uncased weapon. In this case 30 kg TNT were used. This results in a scaled distance of 0.48m/kg$^{1/3}$. Besides a scabbing crater on the outside and some smaller cracks on the inside no further damage was observed.

Fig. 4 shows a test with a cased weapon. In this case the charge weight was the same as in test No. 2. The difference in result is significant. However, it should be considered that the casing had a square cross section. The wall was breached over an area of about 2.10 m width and 60 cm height.

Fig. 5 shows a test similar to test No. 3. However, in this case the casing had a circular cross section and the explosive consisted of 26.6. kg PETN. Using an equivalent weight factor of 1.3 the scaled distance was the same as in shot No. 1. The wall was also breached. The reason for not obtaining a clearly localized breach might be that the wall acted like a cantelever because of the fact that the entrance opening was a weak point in the load-bearing system. The spalling layer had a thickness of about 10 cm.

Fig. 6 shows the result of the same test with a smaller weapon. The charge weight was 5.5 kg PETN. With this the scaled distance became about 0.46 m/kg$^{1/3}$. The damage was a limited spall down to a depth of about 15 cm. The spalling layers had a thickness of about 7 cm. The area of damage was about 60 cm wide and 40 cm high.

Fig. 7 shows the result of a full scale test with a MK83. The charge weight was 202 kg Tritonal which results in a scaled distance - using 1.0 as equivalent weight factor - of about 0.51 m/kg$^{1/3}$. The damage was a limited spall down to a depth of about 10 cm within an area of about 2.5 m by 40 cm.

Table 1 gives a summary of the test data.

As all tests showed more local effects than overall reaction I am going to deal with the local damage only.

3. Theories

3.1 Loading of the Wall

A comparison of tests No. 2 and No. 3 (though with a square casing) and No. 4 proves that the contribution to the total load applied to the wall by fragmentation cannot be neglected. Changing one parameter only - i.e. adding a case - the damage to the wall increases from almost no damage on the inside to a total breach of the wall.
The same fact was also determined in Ref. 2. Fig. 8 shows a summary of the work which was done for that report and shows a comparison of the extent of damage for cased and uncased charges. Using this graph there is a fairly good agreement with the results. Only the full-scale test (No. 6) and the test using C4 (No. 1) do not match. Test No. 6 should have yielded a breach instead of spalling. However, the deviation is not too drastic. The result of test No. 1 does not match at all. According to the graph the result should have been spalling only; instead we got a breach.
It should be noted that this graph is strictly based on test results and thus certain limitations have to be observed. No variation of e.g. concrete quality, percentage of reinforcement, casing thickness etc. is considered. However, the tendency of an increased damage when having fragmentation is also shown by this graph.
Thus, the conclusion is that for further calculations a combined loading caused by blast as well as by fragmentation has to be considered.

3.2 Pressure-Time History for a Cylindrical Charge

Due to the lack of reliable data to calculate the pressure-time history for cylindrical charges one has to use other procedures. One possibility might be to use the graphs for hemispherical charges - e.g. Ref. 7 - which give fairly good results. However, as it will be shown later on it is important to have a good description of the pressure with respect to the time.
An extended research work concerning this topic was performed in Germany and is described in Ref. 8. However, some of the conclusions - especially the recommended tables - are partially misleading. Therefore they have to be revised which will be done within the next couple of months. In addition to this some work will be done to compare cased and uncased cylindrical charges.
As there is no further theoretical or experimental work available to my knowledge, one has to rely on these experimental data. However, very little data are available for the weapon/structure configuration considered in this paper, i.e. a scaled distance of about 0.5 $m/kg^{1/3}$ ($1.0 ft/lb^{1/3}$).
The problem of measuring data within this range is that we are still in the region of the fire ball and in addition - if fragmentation is involved - very heavy damage is to be expected especially to the gages directly opposite the charge on the wall.
Because of all those difficulties I am going to use a modified experimental pressure-time history using a free field measurement and multiplying it by the reflection factor recommended in Ref. 7.
A summary of all pressure data used for further consideration is given in Fig. 9. Ref. 3 shows that there is almost no difference between an exponential and a triangular type of pressure distribution if spalling is concerned. Thus, for further calculations the triangular pressure pulse - as shown in Fig. 9 with dotted lines - is used.

3.3 Load by Fragmentation

In addition to the blast load the fragmentation contributes a considerable portion to the total load applied to the wall. The most appropriate way available at this time to calculate this load seems to be the one described in Ref. 1 which is supposed to be a revised version of the corresponding chapters in Ref. 7. However, some research work is under progress in Germany to investigate the loading caused by fragmentation. But, because it is very difficult to find an answer due to the influence of statistical effects and the question of scaling fragmentation this investigation may very well take a long time.
Thus, using Ref. 1 we can calculate the general fragmentation parameters like

- fragmentation distribution,
- total number of primary fragments,
- initial velocity,
- area of impact assuming a certain angle of propagation.

After that the fragments are grouped according to their weight. For each group we can calculate

- average fragment weight,
- impact velocity,
- arrival time,
- number of fragments hitting the area considered,
- penetration depth,
- duration of penetration assuming that the fragment is decelerated linearly from its impact velocity at the surface to zero at a calculated penetration depth,
- pressure applied to the construction member resulting from the penetration.

Summarizing all fragmentation groups one gets a pressure-time history caused by fragmentation only.
We have been using a computer program for the procedure described above. So we got a representative pressure-time history as shown in Fig. 10.
It should be considered that this load is strictly based on theoretical considerations

and that it represents a statistical average. However, at the present time it seems to be the most appropriate way to solve the problem, though it needs to be verified by experimental work.

3.4 Combined Impulse

The combined pressure-time histories for tests No. 4, 5, and 6 are shown in Fig. 11 and give a general view comparing both pressure pulses.
In any case the blast load hits the structure first. Thus, as it will be shown later on the fragments are hitting a possibly weakened structural member.
It can also be seen that the load caused by fragmentation is heavily dependent on the standoff distance. Though in all three tests considered in this chapter the scaled distance - and with this the peak blast pressure - is the same, the pressure peak as well as the arrival time and the duration of the pressure pulse caused by fragmentation vary considerably. Ref. 4 gives some parameters for scaling the penetration processes. Obviously in this case some of the boundary conditions are violated. Certainly the shape and weight of the fragments vary as well as the impact velocity.
More research work has to be done to investigate the problem of scaling the loading caused by fragmentation.

3.5 Spalling Mechanism

The most common theoretical solution for calculating spalling effects is described e.g. in Ref. 3. The principles of the calculations are to reflect the pressure wave after letting it travel through the structural member to the free inner surface. The magnitude of this reflected wave - a tensile wave - might be sufficient to produce fractures near the surface. Ref. 3 gives a praphical method of solution as well as an anlytical one. For a combined blast-fragmentation impuls it might be more appropriate to use the graphical one.
However, some assumptions have to be made to simplify the calculation. At first, at the free surface normal reflection will be considered only. Second, a change of the duration of the pressure wave will be neglected. Third, a certain attenuation will be considered which is assumed to be about 10% due to material properties and geometrical configurations.
To calculate the thickness of the spalling layer as well as the spalling velocity it is necessary to know the tensile strength of the material of the structural member. As the tests dealt with in this paper were conducted against concrete targets the dynamic tensile strength of concrete has to be determined. This is a difficult problem because of the fact that concrete is a very inhomogenous material. Though there is a procedure to determine the concrete tensile strength the results are at least questionable.

Thus, one commonly assumes a static tensile strength of about 10% of the compressive strength. As shown in Fig. 12 - taken from Ref. 9 - the dynamic compressive strength is dependent on the loading rate. For these tests one has to assume a pressure rise time which will be in the range of about 0.05 msec. Thus, based on a peak pressure of about 400 bar = 5690 psi the rate of stress is about 10^8. With this, we are outside the range given in the graph and one has to extrapolate. The increase of the static tensile strength will be about 350%. With this the tensile strength becomes

$$\sigma_c = 0.1 \cdot 250 \cdot 3.5 = 87.5 \text{kp/cm}^2$$

for test No. 1 and

$$\sigma_c = 0.1 \cdot 500 \cdot 3.5 = 175 \text{kp/cm}^2$$

for tests No. 2 to 6.
However, by calculating the spalling effects one has to observe that the limit velocity of the concrete is not exceeded. The amount of this limit velocity is about 15 m/sec. If this value is exceeded the concrete will be blown out and a breach will be the result.

4. Application of the Theory

Assuming a triangular pressure distribution within the wall as mentioned above one gets the pressure wave/structure configuration as shown in Fig. 13 e.g. for test No. 4. As can be seen, the damage mechanism caused by the blast wave takes place first and after that the pressure wave caused by fragmentation hits a weakened wall. This fact explains the increase of damage by cased charges. To calculate the dimensions of the pressure wave, i.e. expecially the length, a seismic velocity for concrete of about 3400 m/sec was assumed.
With the formulas given in Ref. 3 one can easily calculate the thickness of the spalling layers as well as their velocities. Because of the fact that the rise time for the pressure waves is assumed to be zero the thickness of the different spalling layers is equal and the velocity decreases by a fixed amount for each layer. Table 2 gives a general view of all tests calculated. The results agree fairly well with the test results. However, in no case the calculated spalling velocity exceeds the limit velocity as mentioned above.
This table also shows that scaling of fragmentation effects is very questionable. Though all tests were conducted using the same scaled distance the peak load as well as the effect of the fragmentation varied considerably.
In a final step we have several possibilities for calculating the damage process going on. A most appropriate way is to consider the inside wall reinforcement acting as a membrane almost like a spall plate. However, one main problem in considering a membrane type reaction of the reinforcement is that we have to assume a sufficient embedment length. This might be very questionable especially as in the tests dealt with in this paper the weapon was placed at the footing of the wall which apparently might be a

weak point in the structural design.
Unfortunately the time does not allow to go into more detail concerning this calculation procedure.

5. Conclusion and Recommendations

To my knowledge there is at present no better way of theoretically solving the problem of a close distance detonation.
However, because this is a very common threat configuration in standard conventional weapons effects design much more research - theoretically and experimentally - should be performed to get a better knowledge in this area. Some work is under way e.g. within the US Air Force supported by the US Army Waterways Experiment Station and we will have some more tests within the next year in Germany.

However, it should be mentioned that, though the tests described in this paper, produced considerable damage in some cases, we found a very easy-to-construct and cheap method to upgrade the wall by means of berms or concrete slabs. The main objectives of those upgrading systems is to cut the peak of the blast pressure and prevent the fragments from hitting the wall by means of an elastic and compressible design.

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Test No	weight of explosive	type of explosive	equivalent weight factor	cased / uncased	thickness of casing	diameter of casing	scaled distance	vertical reinforcement	concrete compress. strength
	kg				mm	mm	m/kg$^{1/3}$	%	N/mm^2
1	26.6	C4	1.3	uncased	-	-	0.46	0.085	25
2	30	TNT	1.0	uncased	-	-	0.48	0.17	50
3	30	TNT	1.0	cased	6	230 square	0.48	0.17	50
4	26.6	PETN	1.3	cased	6	200	0.46	0.085	50
5	5.5	PETN	1.3	cased	5	105	0.46	0.085	50
6	202	Tritonal	1.0	cased	9	360	0.51	0.3 about	50

Table 1: Summary of testdata

Test No	0.9·P$_{so}$		time of arrival		assumed duration		thickness of spalling layer		spalling velocity 1. layer	
	blast	fragmen-tation	blast	fragmen-tation	blast	fragmen-tation	blast	fragmen-tation	blast	fragmen-tation
	bar	bar	msec	msec	msec	msec	cm	cm	m/sec	m/sec
1	234	-	0.55	-	0.075	-	4.77	-	4.39	-
2	-	-	-	-	-	-	-	-	-	-
3	277	-	0.75	-	0.175	-	18.78	-	4.38	-
4	360	396	0.4	0.8	0.2	0.15	16.53	11.27	6.29	7.12
5	360	495	0.25	0.5	0.15	0.13	12.40	7.81	6.29	9.41
6	360	288	0.8	1.4	0.5	0.3	41.32	30.99	6.29	4.63

Table 2: Calculation results for spalling effects

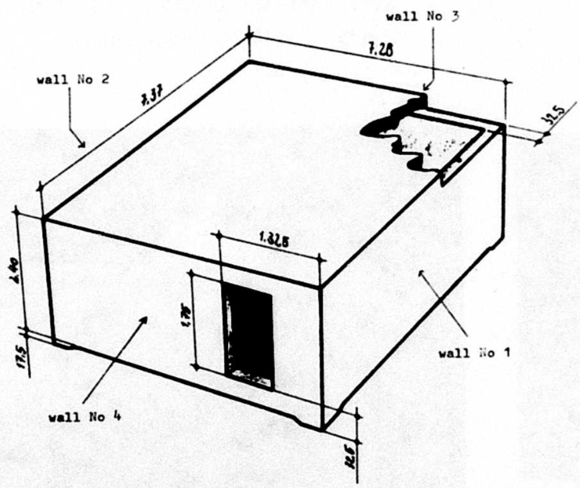


Fig 1:

Example for Modelstructure
(used in Test No 2 to 5)

Fig 2a : Test No1 - outside damage

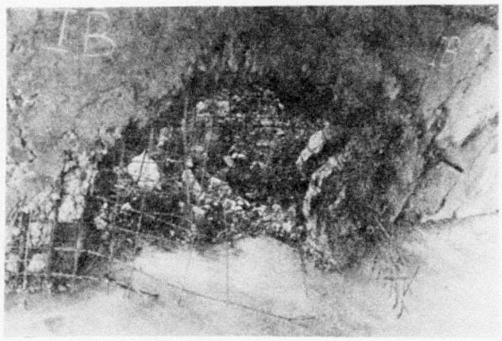


Fig 2b : Test No1 - inside damage

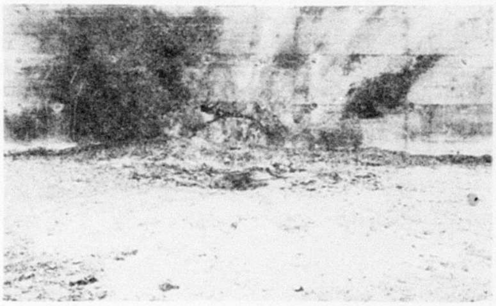


Fig 3a : Test No2 - outside damage

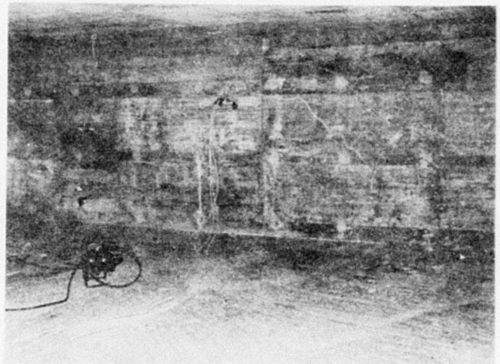


Fig 3b : Test No2 - inside damage

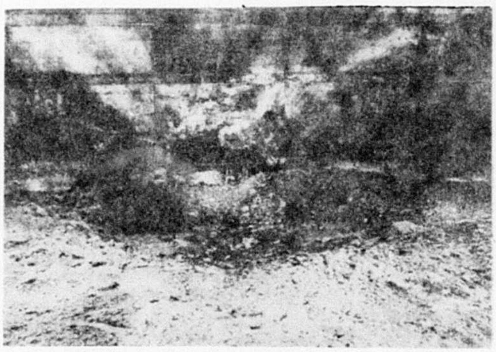


Fig 4a : Test No3 - outside damage

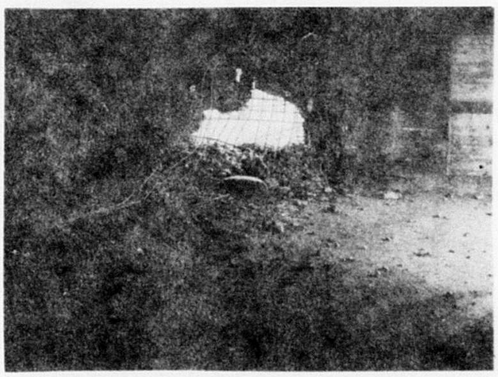


Fig 4b : Test No3 - inside damage

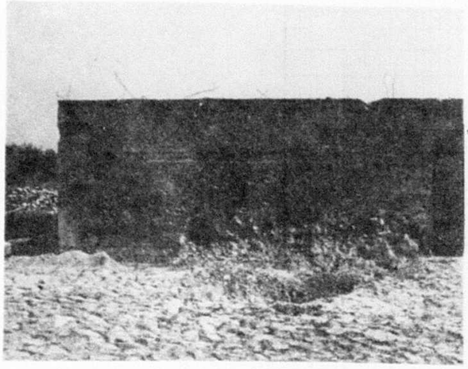


Fig 5a : Test No 4 - outside damage

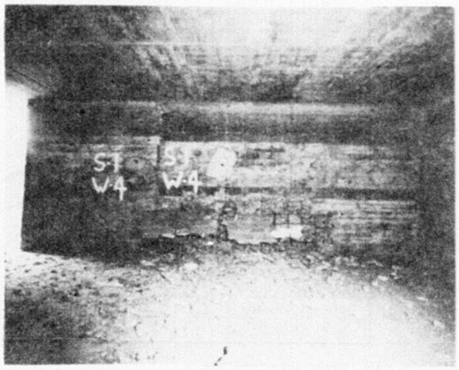


Fig 5b : Test No 4 - inside damage

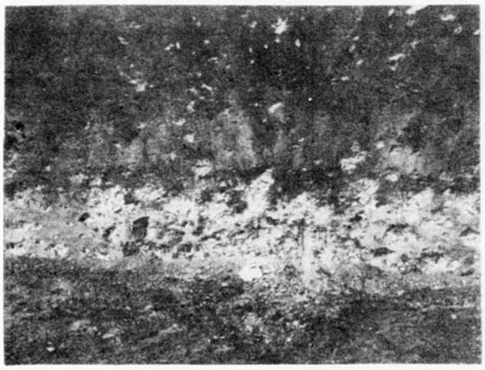


Fig 6a : Test No 5 - outside damage

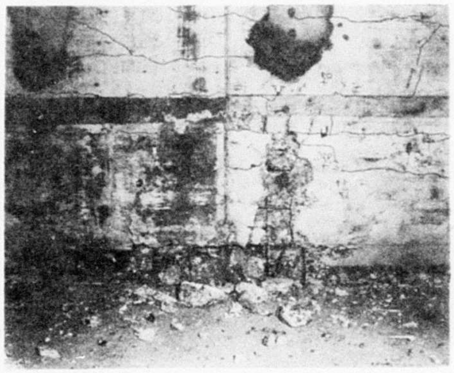


Fig 6b : Test No 5 - inside damage

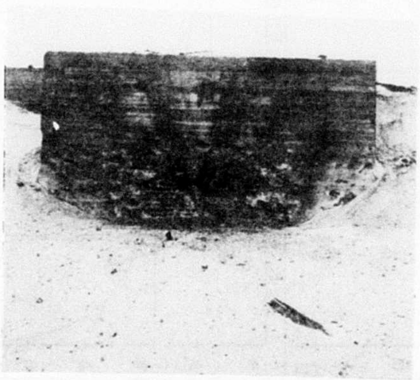


Fig 7a : Test No 6 - outside damage

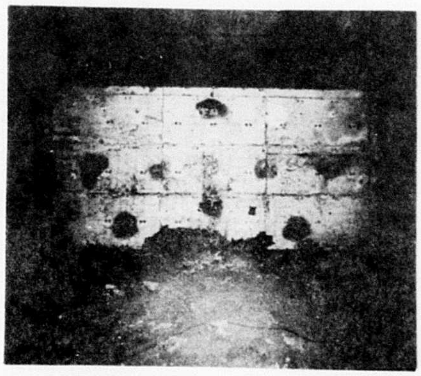
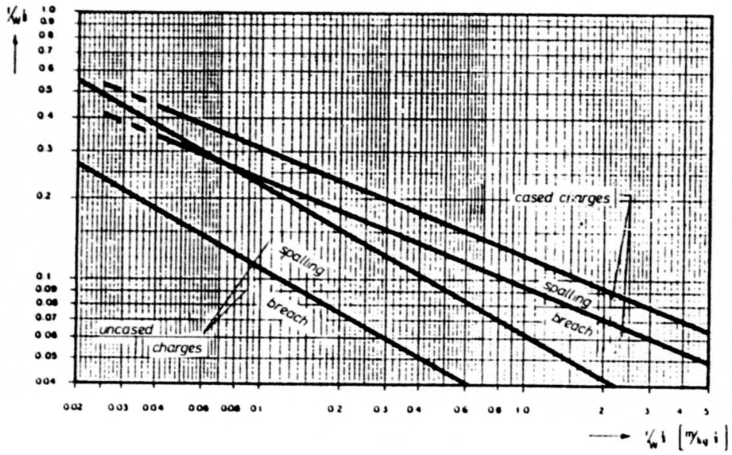


Fig 7b : Test No 6 - inside damage



r = stand off distance (m)
t = wall thickness (m)
w = charge weight (kg)

Fig 8: Damage Classification (according Ref. 2)

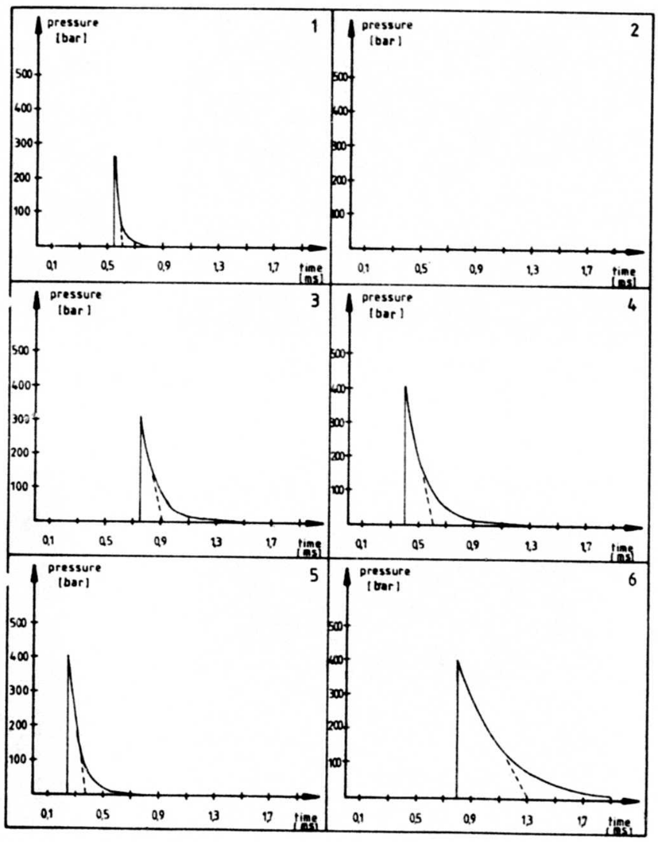


Fig 9: Pressure-Time-Histories caused by blast

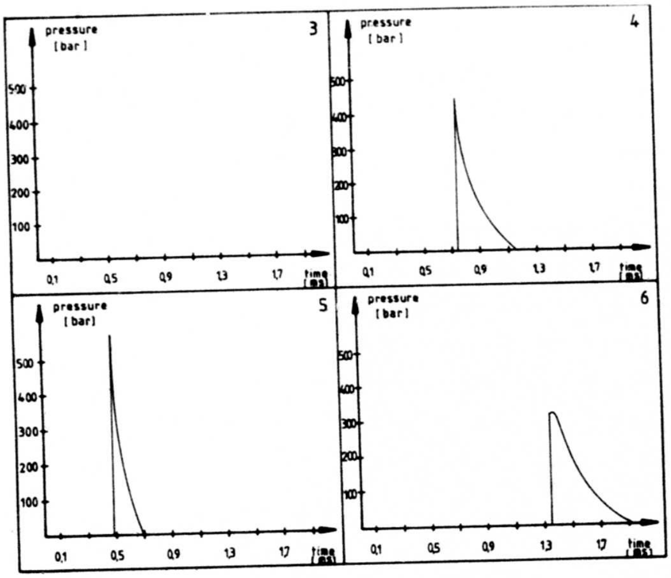


Fig 10: Pressure-Time-Histories
caused by fragmentation

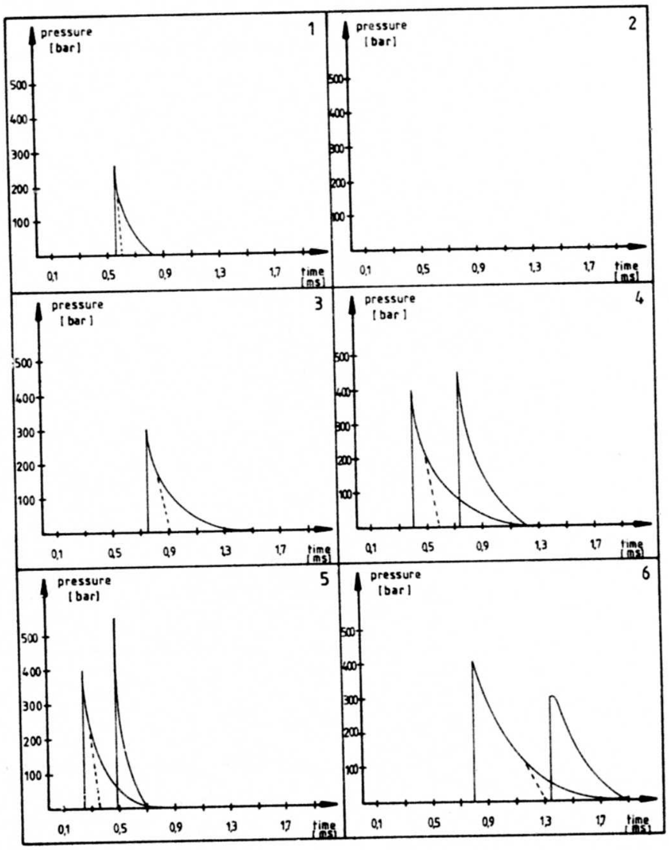


Fig 11: combined Pressure-Time-Histories
caused by blast and fragmentation

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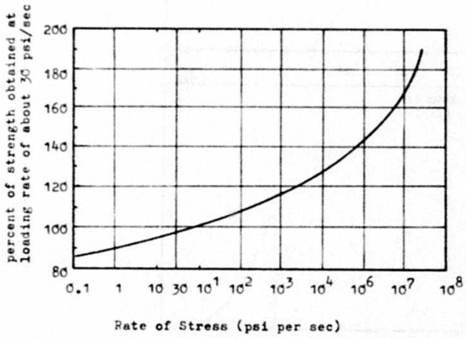

Fig 12: Effect of rate of stressing on the compressive strength of concrete

(taken from Ref 9)

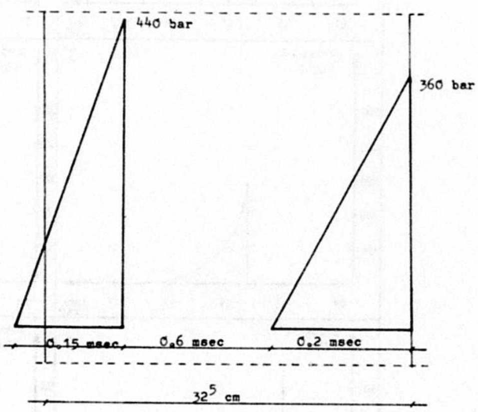

Fig 13:

Pressurewave / Structure Configuration

(e.g. Test No 4)